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Design & development of a machine for dimensional measurement-cum-dismantling of irradiated fuel subassemblies

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Abstract

Periodic performance assessment of selected fuel subassemblies (FSA) in the Fast Breeder Test Reactor (FBTR) at Kalpakkam is carried out through post irradiation examination (PIE) to facilitate life extension of the remaining FSAs to safe and optimum limits. A dimensional measurement–cum–laser dismantling (DMLD) machine has been developed, installed and operated inside the radioactive environment of the hot cells for dimensional measurements and dismantling of highly irradiated FSAs discharged from the reactor. This paper discusses the various constructional features of the remotely operated machine, techniques for remote dimensional measurements, reconstruction of 3-D image, and dismantling of FSAs using laser and diamond wheel.

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Hot cells; remote operation; fast breeder test reactor; fuel subassembly; post irradiation examination; dimensional measurement; dismantling; laser cutting; diamond wheel cutting; profilometry.

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1. Introduction

Radio metallurgy laboratory (RML) was established in Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, India, for PIE of fuel and core structural materials irradiated in FBTR. Irradiation performance assessment provides crucial inputs for the development of advanced materials for future fast reactors which have to play a major role in the energy security of India. Fuel elements which can be safely irradiated to burn-ups of above 100 GWd/t is essential for the economic operation of fast reactors.

A special purpose remotely operated computer controlled dimensional measurement-cum-laser dismantling (DMLD) machine has been developed, tested, installed and successfully operated inside the hot cells of RML to facilitate precise dimensional measurements, and also for the laser based dismantling of FBTR FSAs. The machine uses a touch trigger sensor for dimensional measurements of the FSAs. The surface point data acquired during the dimensional measurements is used for the reconstruction of 3-D profile of the subassembly for the analysis of changes in dimensions due to irradiation. The machine has provisions for longitudinal and transverse cutting of inner and outer hexagonal wrappers of fuel FSAs using either laser beam or motorized diamond wheel. The operation, maintenance and repair of DMLD machine are carried out using the limited dexterity in-cell remote handling devices such as master-slave manipulators (MSMs), power manipulator and overhead crane.

2. Objectives of the machine

The irradiated FSAs from FBTR are highly radioactive. The on-contact γ dose-rate of these FSAs are as high as 5.3×10^3 Sv/h. Therefore, they have to be examined or dismantled inside concrete shielded hot cells using remotely operated devices. The objectives of DMLD machine is as follows:

1. Quantifying the deformation of FSA.
2. Dismantling of FSA for extracting fuel pin bundle.

During their residence inside the reactor, the FBTR FSAs are exposed to the hostile environment of high temperature, high neutron flux, and primary and secondary stresses. This will lead to deformations and volumetric growth of FSAs due to irradiation swelling and creep. Variation of dimensions beyond the design limits will cause fuel handling problems inside the reactor. Therefore when FSAs with new fuel and core structural materials are irradiated in FBTR, performance assessments on typical assemblies are carried out through PIE at pre-estimated intervals, to characterize their irradiation behaviour. Dimensional measurement is one of the many examinations carried out for this.

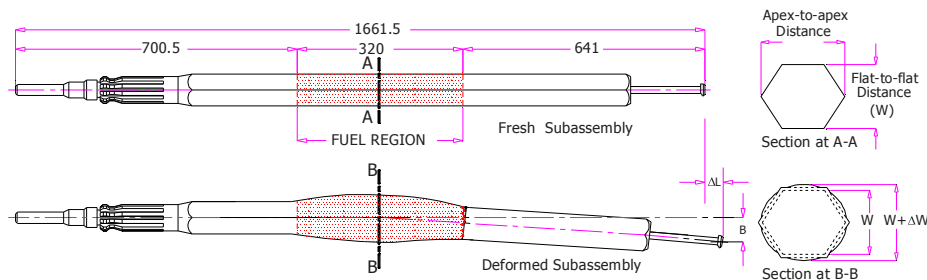


Fig. 1. Normal FSA, and a typical deformed FSA

Fig. 1 shows the dimensions of a normal FSA, and a typical deformed FSA. The major dimensional parameters that need to be measured and evaluated on the irradiated FSA are given in Table 1. It also gives the nominal values, maximum expected changes, causes of changes and the accuracy of measurements needed for meaningful interpretation of the results.

Table 1. Dimensional parameters to be measured on FSA

No.	Dimensional parameter to be measured on FSA	Nominal value	Max. expected increase	Cause of change	Accuracy of measurement
1	Length	1661.5	5 mm (ΔL)	swelling	± 0.5 mm
2	Head-to-foot-misalignment	1.0	7 mm (B)	Differential swelling + creep	± 0.5 mm
3	Flat-to-flat distance	49.8 $^{+0.2}$	0.7 mm (ΔW)	swelling + creep	± 0.025 mm
4	Corner-to-corner-distance	57	1 mm	swelling	± 0.025 mm

FSAs have to be dismantled to extract the fuel pin bundles for PIE of fuel pins. The dismantling of an FSA involves, transverse cutting of the outer and inner hexagonal wrappers of the FSA to disengage the fuel pin bundle from it, and pulling of the fuel pin bundle out of the hexagonal wrapper. Occasionally, longitudinal cutting also become necessary when the bundle remains stuck within the hexagonal wrapper due to the diametrical increase and distortions of the fuel pins.

3.0 Description of DMLD

The machine consists of mechanical system, motion control system and laser system. The mechanical bench is located inside hot cell, while most of the components of the motion control system and the laser system are located out side hot cell in the operating area. The signal, power and fibre optic cables pass through leak-tight penetrations provided on the hot cell wall. Components located inside the hot cells are designed to withstand at least 10^8 rads of gamma ray (1 MeV) dose. General design philosophies applicable for remotely operated equipments in hot cells have been followed [1], [2].

3.1 Mechanical System

The construction of the mechanical system is modular to make it amenable for remote repair / replacement. Assembly of a group of components to perform a particular task forms a module. Some of the modules have sub-modules. The design of the modules is such that, they can be easily removed and replaced remotely using the in-cell remote handling devices. They have lifting bails, assembly features to assure accurate positioning, aligning and mating, and simple locking/unlocking arrangements. Dimensions of modules are such that they can be transferred in/out through the ports available in the cell wall. The design of individual locking/unlocking arrangements is based on how often the replacement of that module is anticipated. It is envisaged that the every module of the machine requires at least one repair or replacement during the life time of the machine.

The mechanical system consists of an X-stage module and an YZ-stage assembly module mounted on a machine bed. Two subassembly holder modules are locked on the X-stage carriage of the mechanical system, of which one is motorised. They are designed to rigidly hold, move (along x-axis), index and rotate (θ) the FSA during various machine operations. They are split type with top loading arrangement. This construction allows lowering and loading of FSA in horizontal orientation into the self centering chucks of these holders from top. After placing the FSA inside the chucks, it is locked to them using MSMs. The chuck design permits the continuous rotation of FSA in clock wise or anti-clock wise direction.

Photographs of the 4-axis mechanical system of the machine are shown in Fig. 2. The Z-stage module of the machine has a provision to alternatively accommodate touch trigger sensor assembly module for dimensional measurements or laser torch assembly module or motorized diamond wheel assembly module to carry out dismantling operations. Table 2 gives technical specifications of the X, Y, Z and θ stages of the machine.

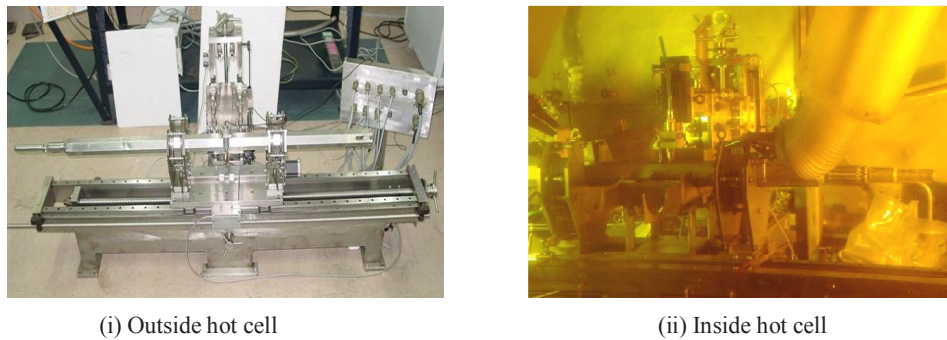


Fig. 2. Photographs of the mechanical system of DMLD machine

Table 2. Specifications of X, Y, Z and θ stages

Stage	Travel	Feedback device	Resolution	Positioning accuracy
X	1350 mm	Lin. Scale	5 μm	$\pm 5 \mu\text{m}$
Y	220 mm	Lin. Scale	1 μm	$\pm 1 \mu\text{m}$
Z	205 mm	Lin. Scale	1 μm	$\pm 1 \mu\text{m}$
θ	Continuous	Nil	0.02°	$\pm 0.02^\circ$

3.1.1 Mechanical system salient design features and technical specifications

The dimensions of the modules are such that they can be taken in to the hot cells for replacement or out of hot cell for repair / final disposal at waste management facility, through the transfer ports (size: 230 mm X 220 mm) provided on the walls of the cells. To facilitate remote operation, maintenance and repair, the machine as a whole was designed to remain in the visible range of the shielding glass window and within the reach of MSMs. The MSM reach diagram of RML hot cell was used to determine the dimensional envelope of the machine and the ideal location of machine on the hot cell floor.

Stainless steel was chosen for the construction of the machine because of its high resistance against corrosion and ease of decontamination. Cables, motors, sensors, limit switches, etc., which can withstand at least 10^8 rads of gamma ray (1 MeV) dose, was used after validation in gamma chambers. Use of some components containing irradiation degradable materials was unavoidable, but they were incorporated as part of easily replaceable modules. High precision linear motion guides and blocks, and ball screws and nuts were used in the fabrication of the X, Y and Z stages. Radiation resistant high precision electronic linear displacement scales were attached to the stages for continuous streaming and display of the machine co-ordinates.

The maximum weight of the modules and sub modules are restricted based on the lifting capacities of in-cell material handling equipments. Maximum weights of sub modules, which require frequent replacement/repair, were restricted to 70 N. This helps in carrying out all operations related to the remote replacement of the sub modules using the MSMs. Maximum weights of heavier modules like X-stage, Y-stage and Z-stage were restricted to 10000 N, which is the lifting capacity of in-cell crane. Pockets and crevices were minimized in the design as they may fix contamination and make the decontamination of the modules tedious.

3.2. Motion control system

Motion control system consists of components such as radiation resistant stepper motors, linear displacement scales, touch trigger sensor, limit switches etc., which are integral with the mechanical system kept inside the hot cell, and stepper motor drives, stepper motor card, IBM PC, motion control software, etc. located outside the cell, in

the operating area. The specifications of the components of the motion control system are given in Table 3.

Table. 3 Specifications of the components of the motion control system

<i>Component</i>	<i>Specifications</i>
Limit switches	2 end limits, 1 home limit
Stepping motors	2-phase bipolar stepper motor, 1.3 Nm
Stepping motor drives	2A/phase, bipolar stepper drive with micro-stepping
Stepping motor control card	PCI-8134, PCI based 4-axis motion control card
Touch trigger sensor	Induction type, Omni-directional, Φ 8 mm ruby ball stylus Accuracy- 1.0 μ m, Repeatability - 1.0 μ m
Motion control software written in C language	Graphic user interfaces : Main menu, profilometry menu, laser cutting menu, diamond wheel cutting menu, settings menu
Electronic linear displacement scales *	Accuracy : X-axis - 5.0 μ m and Y & Z axes - 1.0 μ m
Electronic scales display unit	3-axis display, RS 232 port for data output
IBM PC	Processor: Intel Pentium IV CPU @ 2.2 GHz with FSB @400 MHz

* To provide redundancy, provision has been given in the motion control system to take inputs from the stepper motor controller in case of failure of the linear displacement scales.

3.2.1 Motion control Software

All operations of DMLD machine is carried out by issuing instructions through a computer. A motion control software with user friendly graphic interfaces (GUI) developed using C language is used for this purpose. The software has five GUIs such as main menu, profilometry, laser cutting, diamond wheel cutting and settings menu. All the menus have display fields to display the X, Y, Z and Θ co-ordinates of the touch trigger sensor, and the diamond wheel cutting and profilometry menus have additional display fields to display the co-ordinates of cutting edges of diamond wheel and laser torch respectively.

In each of the GUIs, there are few sub menus. One can enter in a sub menu by clicking on the 'click to enter' command button. Safety interlocks are provided in the software to prevent switching to other sub menus before closing the currently opened sub menu. By clicking on the 'quit' button one can exit from the sub menus.

Main Menu is the opening GUI which appear on the screen as soon as the software is invoked in the computer. It has command buttons to go to the other GUIs, and to carry out the keyboard or mouse mode operation of stages whereas other menus have only mouse mode operation of stages. In the key board mode of operation, user has to input the end point to which a particular stage is to be moved and click on the run button to move the stage. In mouse mode operation, user has to click on the up arrow of a particular stage for its forward motion and down arrow for its reverse motion. In both the modes of operation, at a time only one stage can be operated.

Profilometry GUI has subsections to select manual/automatic scan mode, enter/select path and file name to acquire data/view acquired data, and enter parameters for 2D/3D automatic scanning of FSA. *Laser Cutting GUI* has sub sections to select transverse/longitudinal modes of cutting, and to enter cutting parameters. *Diamond Wheel Cutting GUI* has subsections to select transverse/longitudinal modes of cutting, select profile/ordinary cutting,

selecting path and file name for data acquisition/view the acquired data, and entering the scan/cutting parameters. Profile cut mode of operation facilitate the 2D cutting of the FSA through a path previously scanned using touch trigger sensor. This facilitated cutting of the distorted hexagonal tube without damaging the internals.

4. Dimensional measurements (Profilometry) of FSA

The sectional view of an FBTR FSA is shown in fig. 3. Important measurements made during profilometry are the following:

1. Increase in corner-to-corner distances of hexagonal outer sheath at various cross sections along the length of FSA,
2. Increase in flat-to-flat distances of hexagonal outer sheath at various cross sections along the length of FSA, and
3. Head-to-foot misalignment of FSA

Profilometry involves two steps, scanning of FSA with touch trigger sensor for acquiring the coordinates of surface points and reconstruction of the FSA in 3D modelling environment of CAD software. The reconstructed image can provide all required information such as the maximum extent of deformation, its location etc.

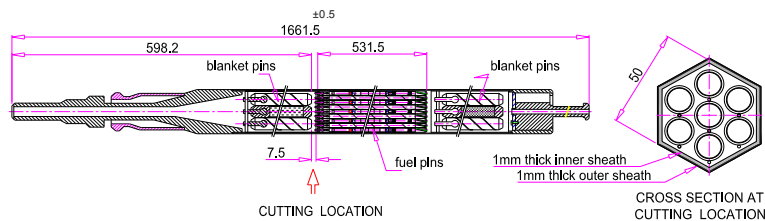


Fig. 3. Sectional view of an FBTR FSA showing cut location for retrieval of fuel bundle

An induction type touch trigger sensor with three styli configured as shown in fig. 4 is used for scanning the surface of FSA for surface point data acquisition. The sensor has two horizontal styli and a vertical stylus in Y-Z plane. The horizontal styli have 8 mm diameter spherical ruby measuring tips and the vertical stylus has a 2 mm diameter cylindrical measuring surface. The scanning of FSA for surface points is done step by step, cross-section wise, by bringing the required axial cross-sections to the Y-Z plane in which the touch trigger sensor moves. A subroutine of motion control software will automatically carry out the scanning and data acquisition from these cross sections. The scheme of movement of touch trigger sensor during automated scanning of a cross section is shown in fig.5.

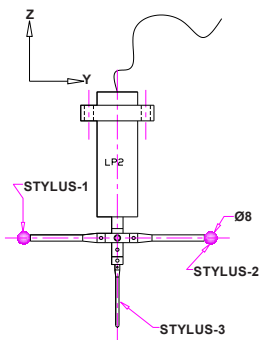


Fig.4. Touch trigger sensor

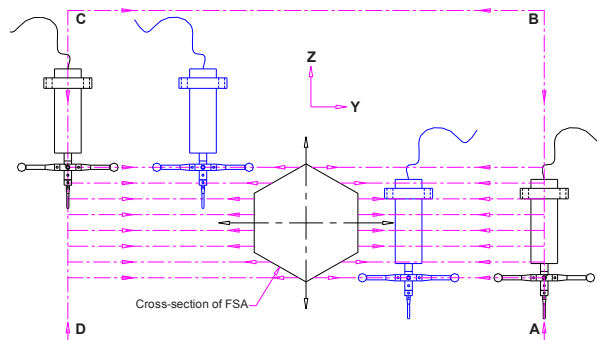


Fig.5. Movement of touch trigger sensor during automated scanning

During the scanning, the software will move the touch trigger sensor continuously towards the FSA from two pre-fixed datum lines AB and CD, by operating the Y-stage. When the tip of the touch trigger sensor comes in

contact with the surface of FSA, an electrical output is generated. The scanning program makes use of this output to stop the forward motion of the sensor, acquire the surface point co-ordinates to a file and trigger the routine for the next surface point acquisition. Two types of surface scanning provisions are given in the GUI - auto scanning and manual scanning. Auto scanning is used to acquire surface point from various cross sections along the length of the FSA for the construction of 3D profile. Manual scanning is used for the precise measurement of corner-to-corner distances at various locations along the length of FSA.

4.1 Auto scanning

In auto scanning, various cross-sections of the FSA are scanned and surface point co-ordinates are acquired as per the scan parameters specified in the GUI of profilometry. It is not possible to scan and acquire data from diametrically opposite sides of a cross section with a single stylus. Therefore stylus-1 and stylus-2 have to be used respectively for the scanning of right side and left side of the cross sections. The data acquired using stylus-2 has to be normalized to that of the data from stylus-1 or vice versa. This necessitates the determination of Δx , Δy and Δz correction constants for the normalization. A precision rectangular block was fabricated and used for finding out these constants. The block is currently used to check the values of these constants each time the touch trigger module is reloaded in the machine. The data from both styli is saved to a script file for reconstructing the cross section.

The path of movement of touch trigger sensor around a cross section during auto scanning of a full cross-section is shown in Fig. 6. After completing the scanning of a particular cross section, the FSA is moved one incremental distance along the X-axis to bring a new cross-section to the plane of the touch trigger sensor, and the scanning and data acquisition is repeated. The process is continued till the surface point data from the last cross section is acquired.

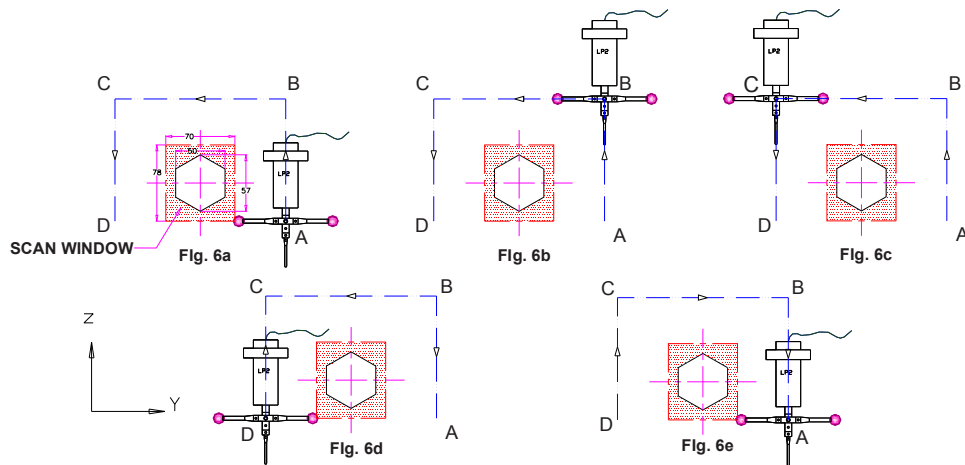


Fig. 6. Path of movement of touch trigger sensor around a cross section during auto scanning

The script file generated during auto scanning is run in 2-D model space of ACAD to reconstruct the cross sections. The machine is capable of reproducing the cross sections with an accuracy of $\pm 20 \mu\text{m}$. Typical reconstructed cross-sections of an FBTR FSA are shown in Fig. 7. The dimensional changes are measured from these plots. It can be seen from the reconstructed cross sections that the flat-to-flat distances have grown up to 0.6 mm at the fuel column region. The maximum allowed increase in flat-to flat distance is 0.7 mm.

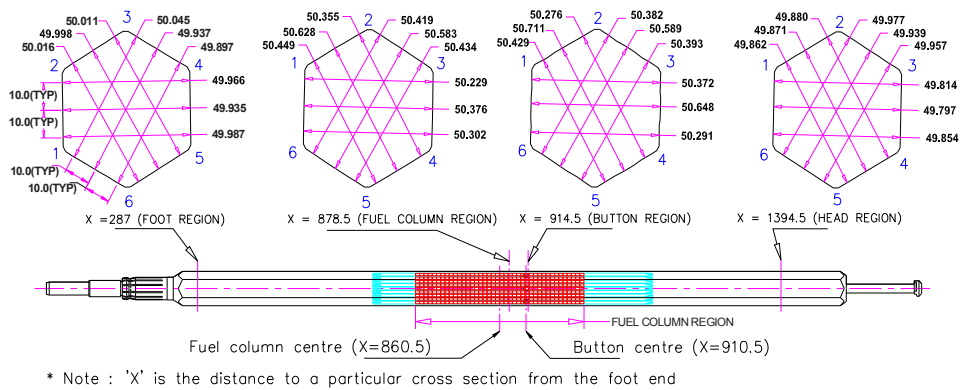


Fig. 7 Reconstructed cross-section of FBTR FSA

4.2 Manual scanning

The corner-to-corner distances cannot be measured directly from the cross sections reconstructed using the data acquired by auto scanning as it is not possible to acquire sufficient number of points from the corners for the precise reconstruction of the corners. Manual scanning is devised for the accurate measurement corner-to-corner distances. The movement of touch trigger sensor during manual scanning of a cross-section is illustrated in fig. 8. The touch trigger sensor stylus-3 tip is used for manual scanning of FSA.

4.3 Reconstruction of 3-D profile

The cross sections of the FSA are plotted by running the script file created during auto scanning of FSA in 3D model space of ACAD. The axis of the FSA is constructed by joining the centroids of the area enclosed by these cross sections. The deviation of the head end of the FSA from the extension of the axis of the foot region of the FSA is assessed from the plot and treated as the head-to-foot-misalignment. The surface profile of the FSA is constructed by extruding the individual cross sections along the axis of FSA. Reconstructed 3-D image of a typical irradiated FSA is shown in fig. 9.

5.0. Cutting and dismantling of FSA

DMLD machine has provision to cut FSA by laser beam and a motorized diamond wheel is also provided for redundancy. The pre-fixed cut location for the retrieval fuel bundle from the FSA is shown in fig. 3.

5.1 Laser cutting

Laser-based cutting is preferred over other techniques for dismantling of FSA as it has various advantages such as non-contact nature of cutting, fast cutting, ease of remote operation, minimum remote repair/replacement of parts, absence of coolant and minimum generation of waste such as dust, chips, etc. over other techniques [3]. A 150W, pulsed Nd-YAG supplied by RRCAT, Indore, was used for laser cutting of FSA. It consists of components such as Nd-YAG lasing cavity, power supply, control panel, chiller and a fiber-optic cable fitted with cutting nozzle. Quartz optic fibre (400 μm) was selected for laser beam delivery for stable performance in highly radioactive hot cell environment. [4]

A laser torch module held in the Z-carriage of DMLD machine was used for cutting of FSA. The laser module consists of a laser torch fixed on the slider of a vertical slide. This construction allows gravity assisted up and down movement of the laser torch during the cutting operation. This arrangement together with the roller arrangement attached near tip of the torch help to maintain a constant gap between the torch tip and the FSA surface during cutting. Automatic constant gap maintaining arrangement used for standardization of procedure is shown in fig. 10.

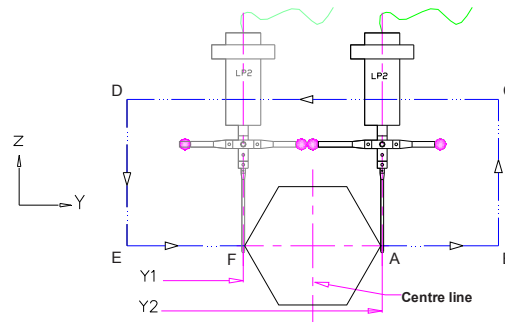


Fig. 8. Movement of touch trigger sensor during corner-to-corner scanning a cross-section.

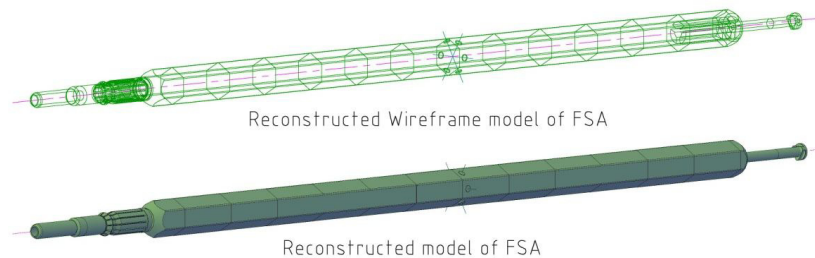


Fig. 9. Reconstructed view of irradiated FSA

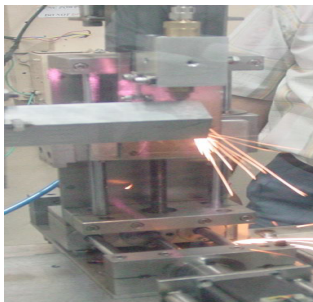


Fig. 10. Automatic gap maintaining arrangement

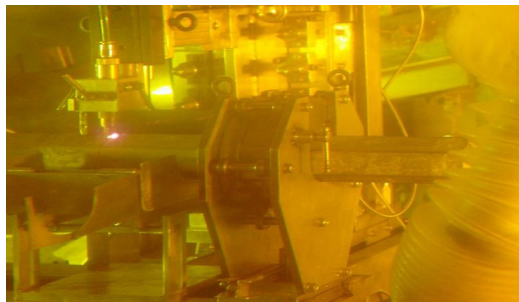


Fig. 11. Laser cutting of FSA inside the hot cell

The laser cutting GUI has provision to select either longitudinal (along x-direction) or transverse-Y (along y - direction) or transverse-W (along Θ -direction) mode of cutting of FSA. After switching on the laser, the FSA is moved with respect to the torch until the cut end point reaches the tip of laser torch by operating X-stage in case of 'longitudinal', Y stage in case of 'transverse-Y' and rotating the motorized FSA holder in case of transverse-W. A photograph taken through the 1.2 m thick shielding glass window (fig. 11) shows the FSA being cut using the laser torch inside RML hot cell.

The optimized parameters [5] for the cutting of AISI 316 LN 2 mm thick wrapper of FBTR FSA are as follows:

Pulse energy	-	50J
Pulse duration	-	2 ms
Repetition rate	-	20 to 30 Hz
Surface speed	-	2 mm/s, and
Purge gas pressure	-	12 kg/cm ²

5.2 Diamond wheel cutting

Diamond wheel cutting of FSA was carried out using a motorized diamond wheel module held in the Z-carriage of DMLD. The module consists of a 250 mm diameter wafer-thin diamond-wheel, a DC motor and a pair of bevel gears. In the module, there are two spring loaded, rotary ball tipped followers on either side of the cutting wheel, which actuate a linearly variable differential transformer (LVDT) to control the depth of cut, so that the internals are not damaged under any circumstances. The bottom ends of the followers are at the same elevation as that of bottom edge of the cutting wheel. Therefore during cutting, as the cutting wheel plunges into the hexagonal wrapper during cutting, the followers actuate the LVDT to provide the instantaneous values of depth of cut.

GUI for Diamond wheel cutting of FSA has provision for selecting either longitudinal (along x-direction) or transverse (along y-direction) mode of cutting. It has provision for cutting through a path scanned with the touch trigger sensor for cutting of distorted FSAs, without damaging the fuel pins inside.

Because of operational considerations, no liquid coolant is allowed inside the hot cells and hence dry cutting has to be carried out. Cutting is done at a low speed to reduce heat generation. The optimized parameters for cutting are: cutting speed = 150 rpm and feed rate of 5 mm/min. A circuit breaker is provided in the motor circuit for overload protection.

6.0 Conclusion

A computer controlled Dimensional-Measurement-cum-Laser Dismantling (DMLD) machine has been developed, installed and successfully used for remote profilometry and laser based dismantling of various sub assemblies in the highly radioactive environment of the hot cells of RML. Along with other PIE results, the results of profilometry provided information on the irradiation behaviour of FSAs discharged from FBTR. The experience gained during the development of the machine has been invaluable and will remain as a benchmark for the development of other hot cell equipment of this nature for future hot cell applications.

The constraints/challenges involved and overcome during the design of the system are:

- Compactness, remote operability and modular construction to suit hot cell operational constraints.
- Selection of components to withstand high radiation environments.
- Reconstructing the surface profile of a highly deformed component and estimating the extent of deformation as compared to the original regular profile that it had prior to irradiation.
- Dismantling a highly deformed FSA without damaging the internals.
- Need for using a split type holder for easy loading, holding and rotating deformed FSAs. Holding and rotating a long tubular object on two individual holders, one of which is motorized, becomes a complex operation when the object has a distorted central axis, since it induces excessive stresses in the object as well as on the holders. The flexibility provided in the existing holders has to be enhanced through further design modifications to accommodate higher distortions in future.

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